Investigation of Propellant Sloshing and Zero Gravity Equilibrium for the Orion Service Module Propellant Tanks

Amber Bakkum[1], Kimberly Schultz[1], Jonathan Braun[2], Kevin M Crosby[1], Stephanie Finnvik[1],
Isa Fritz[1], Bradley Frye[1], Cecilia Grove[1], Katelyn Hartstern[1],
Samantha Kreppel[1] and Emily Schiavone[1]

[1]Department of Physics, Carthage College, Kenosha, WI
[2]Lockheed Martin Space Systems Company, Houston, TX

August 15, 2010

Abstract

We study fluid slosh in the Orion Service Module propellant tanks. Resonant slosh frequencies were measured as a function of tank fill-fraction in a scaled model of the tanks. We carry out both computational and theoretical calculations of resonant slosh frequencies, and find reasonable agreement between experiment and prediction. We measured fluid slosh in $2-g$, $1-g$, Martian gravity ($1/3-g$) and lunar gravity ($1/6-g$). Using the software FLOW-3D, we established free-surface configurations in zero gravity of both the model and the full scale Orion SM tank. In addition, we measured formation times of the equilibrium free surface configuration. FLOW-3D calculations suggest that the zero-g free surface configuration consists of two separated fluid volumes.

1 Introduction

In fluid dynamics, *slosh* refers to the movement of liquid inside a hollow object. Slosh control of propellant is a significant challenge to spacecraft stability. Mission failure has been attributed to slosh-induced instabilities in several cases [Robinson,1964], [Wade, 2010], [Space Exploration Technologies Corp., 2007]. While propellant masses are highest in the initial phases of a mission (launch and orbital insertion), slosh control is particularly important in the latter stages of the lunar return mission envisioned in the Constellation/Orion

---

The authors gratefully acknowledge the Wisconsin Space Grant Consortium for financial support, Lockheed Martin Space Systems Company and the Reduced Gravity Office at NASA Johnson Space Center for support of the Systems Engineering Educational Discovery (SEED) Program and the Carthage College Summer Undergraduate Research Experience (SURE) Program. The authors wish to thank Professors Doug Arion and Brian Schwartz for useful conversations and insights.

program.

The Orion capsule serves as the crew launch and return vehicle of the Constellation program and consists of a crew module (CM) and service module (SM). In addition to housing thrusters, propellant and oxidizer for lunar return maneuvers, the SM provides power and life-support services to the Orion spacecraft. In support of its main engine, the Aerojet AJ-10 rocket engine, the SM contains two propellant and two oxidizer tanks with a total launch mass of 8300kg of propellant and oxidizer [NASA, 2010]. The bipropellant system consists of mono-methyl hydrazine (MMH) and the oxidizer N_2O_4 (NTO). As a substantial portion of the initial weight of the SM is propellant/oxidizer, an understanding the slosh dynamics in the SM tanks is critical.

As the propellant level decreases throughout a mission, the effects of sloshing forces on the remaining fuel become more prominent. When the tank is full or nearly so, the fuel lacks the open space to slosh. However in the latter stages of the mission, when most of the fuel has been consumed, the fuel has sufficient volume to slosh and possibly disturb the flight trajectory. This sloshing can ultimately lead to wobble in a spinning spacecraft and self-amplifying oscillations that can result in failure of individual instruments or failure of the entire structure. The dynamics of a fluid that interacts with the walls of its container are complicated and challenging to predict. The effects of sloshing on bodies in motion are significant and in some cases devastating. These effects remain prominent even when the propellant volume represents only 0.3% of the total spacecraft mass [Vreeburg, 2005].

Due to the significance of slosh dynamics, a considerable amount of research has been conducted on this topic over the past sixty years. Graham and Rodriguez conducted the first study specifically related to propellant slosh [Graham, 1952]. This research investigated the effect of fuel slosh in aircraft in response to simple harmonic motion from plane pitching and yawing. The results facilitated a general understanding of propellant slosh dynamics.

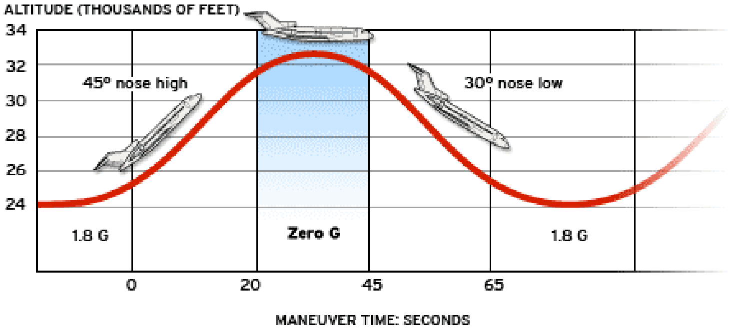
In 1964, a study at the Lewis Research Center in Cleveland, Ohio analyzed experimental sloshing characteristics by relating movement of sloshing liquids to an effective pendulum mass [Sumner et al, 1964]. The researchers employed a scaled version of a Centaur liquid oxygen tank, which was a spherical vessel with a cylindrical portion along the major axis of the tank. Three model tanks with varying complexity were tested. The initial setup was a clean or empty tank with no internal structures. The second setup consisted of an unbaffled tank with a thrust barrel, fill pipe, annular spring ring and a vent pipe. The final tank included a baffle near the center of the tank in addition to the internal structures from the second setup. When compared the clean tank, it was found that the fundamental frequencies of the liquid were reduced due to the thrust barrel in the unbaffled tank. This research is relevant to our project as it provided a considerable amount of information in relation to damping slosh dynamics in a $1-g$ environment. However, research conducted in variable gravity conditions is more pertinent to fluid dynamics in space.

In 1969, Salzman and Masica conducted research that provided data for slosh dynamics under variable low-gravity conditions at the Lewis Research Center [Salzman, 1969]. In particular, the lateral sloshing resonant frequencies in cylindrical tanks were studied as a function of Bond number, a parameter that describes the relationship between gravitational forces and surface tension. The results suggested that for liquid depth ratios (height of the liquid/radius of the tank) less than two, the natural resonant frequency of lateral sloshing is directly proportional to the liquid depth. The study also found that the zero-g liquid equilibrium configuration was reached in less than 50ms for cylinders ranging in radii from 1.59cm to 2.54cm. Because of those results, we conjectured that we could see the equilibrium free surface configuration in our tank within 25s of zero gravity.

We report here the results of an experiment to perform a linear sloshing analysis on a scale model of the SM downstream propellant tanks, to examine the free surface configuration of the same tank in a zero-gravity environment, and to determine the free surface formation times of the liquid in the tank.

2 Parabolic Flight

Our experiment was conducted aboard a microgravity aircraft commissioned by the NASA Reduced Gravity Office (RGO). In order to simulate a zero-g environment, the aircraft flies a set of parabolic flight maneuvers illustrated in Fig. 1. As the plane crests the top of the parabola, the occupants and experiments begin to experience weightlessness. The aircraft then begins a free fall towards the earth in a path that follows an elliptical orbit and lasts approximately 25s. The payload is subjected to weightlessness because it is falling at the same rate as the plane and experiences no ground reaction force from the body of the aircraft.



SOURCE: The Zero Gravity Corporation

Figure 1: A parabolic flight path indicating the zero-g and high-g phases of the trajectory. The aircraft pitch angle determines the gravity field the payload experiences.

3 Research Objectives

It is important to understand relevant fluid properties that will be addressed in this paper. The *Bond number* of a liquid confined in a container of characteristic length L is a dimensionless quantity that describes the relationship between gravitational forces and surface tension as seen in Eqn. 1:

$$B_0 = \frac{\rho g L^2}{\sigma}, \tag{1}$$

where ρ is the density of the liquid, g is the gravitational acceleration experienced by the liquid, and σ is the surface tension of the liquid.

The *contact angle* (θ_c), illustrated in Fig. 2, is the angle at which a liquid meets a solid surface. Contact angle is a function of the cohesive forces within the liquid and the adhesion between the gas and liquid as well as the surface and the liquid. Strong adhesive forces tend to flatten the drop, leading to a smaller contact angle. A contact angle of less than 90 degrees is said to be wetting, and a contact angle of more than 90 degrees is said to be non-wetting. A key research objective is to determine a useful propellant simulant that exhibits the same θ_c as MMH on aluminum.

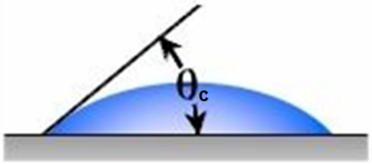


Figure 2: The contact angle of a fluid on a solid surface.

In a zero gravity environment, propellant does not remain at the bottom of the tank, but instead establishes a new configuration within the tank. These *zero-g surface configurations* and their formation times depend on tank geometry and internal structures. If there is an absence of fluid near the intake valve at the bottom of the tank, the spacecraft's engines may fail. To combat the effects of zero gravity on the fluid, the use of reaction control system (RCS) thrusters may be necessary to ensure that fuel is constantly present near the fuel intake valve. In order to properly use the RCS thrusters, the free surface configurations and their formation times for different fill levels must be known. The free surface formation time for a liquid is the time for the fluid surface to obtain its equilibrium shape after a reduction in gravitational acceleration [Dodge, 1967].

The *settling time* of the fluid is an important property and depends on the fluid characteristics, tank design, and Propellant Management Device (PMD) design. The settling time is the amount of time it takes for a liquid to transition from a zero-g surface configuration to the bottom of the tank. The settling time data will determine if the use of RCS thrusters is necessary to reach a faster settling time for proper fuel feed rates. More importantly, settling time data will validate current computational models and PMD designs.

Our research objectives were as follows:

1. to carry out a *Linear Sloshing Analysis* to identify frequencies of the fundamental anti-symmetric slosh modes in the Orion SM downstream propellant tanks
2. to establish the zero-g *free-surface configuration* of propellant in the Orion SM downstream propellant tanks
3. to determine forrmation times for free surface configurations.

We examine these questions using standard potential theory, computational modeling and experiment. This report is organized around these research objectives.

4 Experiment Design

We designed and built a 1/6-linear scale model of the Orion SM Downstream Propellant Tank illustrated in Fig. 3.

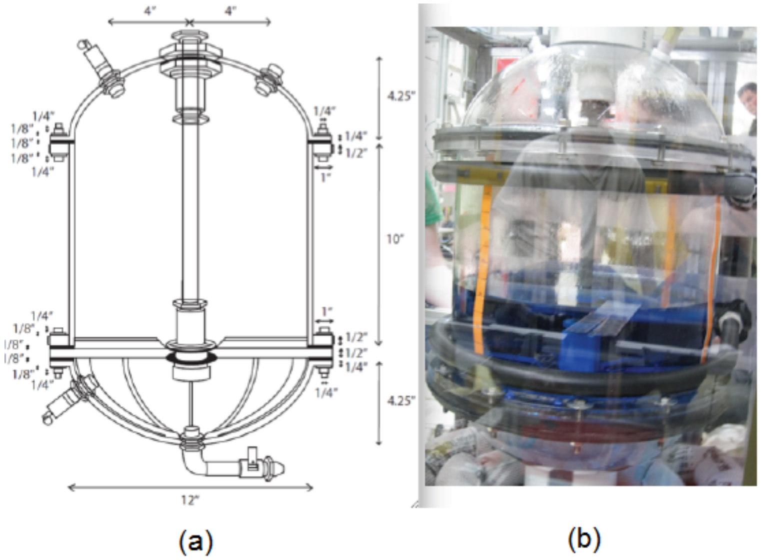


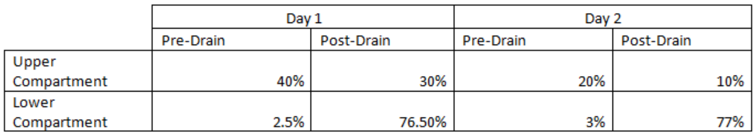
Figure 3: (a) detailed drawing of the internal structures of the model tank; (b) a photograph of the operational tank.

Our model tank consisted of 0.25in thick acrylic cylinder with acrylic domes of similar thickness bolted to each end. The cylinder had a height of 10in and an outer diameter (OD) of 12in. The domes had ellipsoidal vertical cross-sections with a semi-minor axis length of 4.25in (OD). At the bottom of the cylinder, a 0.5in thick circular Lexan plate was bolted between the edge of the cylinder and the bottom dome. The total height of the tank was 19.5in, not including the fill cap at the top of the tank and the manual drain valve at the bottom.

A high-fidelity model of propellant slosh in a reduced-scale tank should preserve the dynamical properties of the fluid in a full-scale tank. To acheive full dynamical equivalence between the two tanks, a set of scaling parameters representing ratios of critical forces must be preserved from model-scale to full-scale. In addition to the contact angle and the Bond number, full dynamical equivalence preserves the value of the Weber number and the Reynolds number. The latter parameter is the ratio of inertial to viscous forces, while the Weber number is the ratio of the inertial forces to surface tension. Preserving the values of each of the three scaling parameters (Bond, Weber, and Reynolds) and the contact angle is generally impossible, and modelers usually choose a simulant fluid to match a single dynamical property such as inertial response.

In our experiment, it was most important to match contact angle and Bond number. The contact angle of MMH on aluminum is approximately 20°. Ethanol and acrylic exhibit a similar contact angle. However, pure ethanol will crack acrylic, so our experiment utilizes a 60/40 mix of ethanol and water. The Bond numbers of the model and full-scale tank differ by an order of magnitude, but are as close as possible given the range of fluids and tank materials availible to us.

We tested four fill-levels in both the upper and lower compartments of the model tank. Halfway through each of the two flight days, we drained propellant simulant from the upper compartment into the lower compartment via the drain plug at the center of the Lexan plate in order to acheive different fill fill-fractions. The fill fractions are displayed in Fig. 4.



	Day 1		Day 2	
	Pre-Drain	Post-Drain	Pre-Drain	Post-Drain
Upper Compartment	40%	30%	20%	10%
Lower Compartment	2.5%	76.50%	3%	77%

Figure 4: This table shows the tested fill-fractions of each compartment of our model tank. The values are percentages of the total volume of the respective compartment.

We collected our data using three mini-DV cameras; two set on the upper compartment, the other to record the lower compartment. They gathered close to 50 minutes of visual data apiece for two days.

5 Computational Fluid Dynamics

Computation Fluid Dynamics (CFD) is the study of fluid dynamics in which algorithms and numerical methods are used to investigate and solve fluid flow problems. To further examine our scale model of the SM downstream propellant tanks, we use a CFD software package called FLOW-3D, a program that models complex fluid flows in many different applications. FLOW-3D uses a process know as the volume of fluid (VOF) method to locate and track the free surface of a fluid. In the VOF method, the fluid and tank geometry are discretized on a mesh. Appropriate boundary conditions based on fluid properties and tank geometry are applied, and the Navier-Stokes equations are solved iteravely on the mesh. The numerical calculations can then be transformed into a picture of what the liquid looks like in the tank, illustrated in Fig. 5.

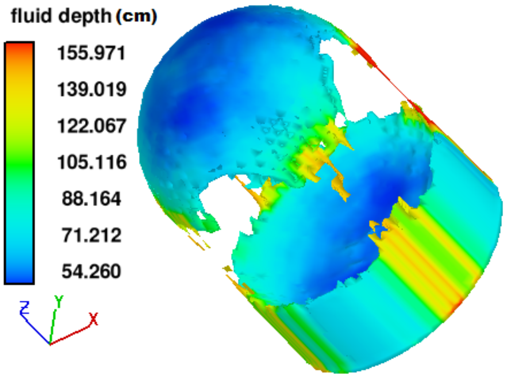


Figure 5: The full-scale tank at 0.8 fill-fraction and 1700 sec. The mesh size is approximately $1cm^3$.

For our purposes, we ran simulations in FLOW-3D to determine the natural resonant frequency of the ethanol at different fill levels, to examine the zero-g free surface configurations for the real and model tanks, and to ascertain the free surface formation time of the fluid.

6 Linear Slosh Analysis

When an impulse is applied to a tank, the fluid will slosh with harmonic motion at a natural frequency that depends on the gravity environment, the tank geometry, and the properties of the fluid. In our experiment, this impulse occurs during aircraft transitions from low-g to high-g. We measured the natural frequencies as a function of the ratio h/R, where h is the liquid height and R is the tank radius.

The spectrum of resonant slosh frequencies in an upright, cylindrical tank can be derived from a standard flow potential theory [Dodge, 2001]. While the tank geometry supports both symmetric and anti-symmetric slosh modes, the anti-symmetric modes are the lowest in energy, and were most frequently observed in our experiments. We therefore restrict our consideration to these modes. The spectrum of anti-symmetric slosh modes in a cylindrical tank are given by

$$f_{mn}^2 = \frac{1}{4\pi^2}\frac{g\xi_{mn}}{R}\tanh(\xi_{mn}h/R), \qquad (2)$$

where g is the acceleration of gravity, ξ_{mn} are the roots of the Bessel function of the first kind (we used ξ_{10}, the lowest non-vanishing solution), h is the height of the liquid, and R

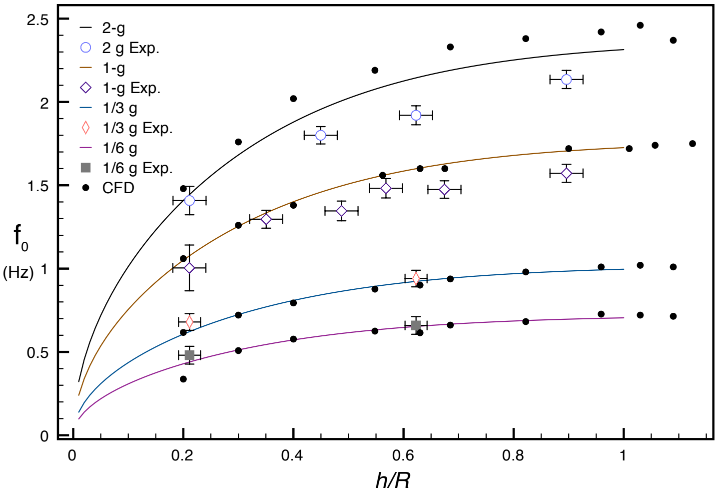


Figure 6: The relationship between natural frequency and fill fraction (h/R). The solid lines are derived from Eqn. 2 at $2-g$, $1-g$, Martian gravity ($1/3-g$) and Lunar gravity ($1/6-g$). The solid points are from FLOW-3D at those fill fractions. The open points are the experimental data measured using the video data. The horizontal error bars indicate uncertainty in height measurement, while the vertical error bars represent standard error in frequency measurements.

is the radius of the tank. Eqn. 2 is derived from the velocity potential for ideal fluids in cylindrical tanks.

Using the FLOW-3D software, we calculated the natural slosh frequency of the computer generated model tank at the various gravity environments and fill levels. Tank models were generated with and without axial mass gauging probes running the length of the upper compartment of the tank. The presence of the mass gauging probe had no discernible effect on the resonant frequencies. In general, we find congruity between theory, CFD, and experiment.

We looked for the natural frequencies of the anti-symmetric mode because it is a low energy formation and the waves carry the most momentum [Abramson, 1966]. Since it carries the most momentum, the anti-symmetric mode is most likely to disturb a spacecraft trajectory and be most dangerous.

7 Free Surface Configuration and Formation Time

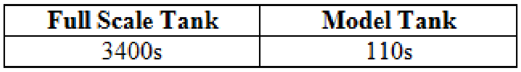
The *formation time* is the time a fluid takes to reach its zero-g surface configuration. In a circular cylindrical tank, the formation time can be calculated using Eqn. 3. Formation times in a cylindrical tank can be estimated from the emperical relation [Dodge, 2001]

$$t_s = \frac{R_0^2}{\nu} \frac{10^B \xi^A + 0.01\alpha^2}{1+\alpha^2} \tag{3}$$

where ν is the kinematic viscosity, R_0 is the radius of the tank and

$$\begin{aligned} \alpha &= \frac{1-\sin\theta_c}{\cos\theta_c} \\ A &= 0.28 + 2.2\alpha - 1.2\alpha^2 \\ B &= 3.9A - 3.32 \\ \xi &= \nu\sqrt{\frac{\rho}{R_0 \sigma \alpha^2 \cos\theta_c}}. \end{aligned}$$

with σ as the surface tension and ρ as the density.



Full Scale Tank	Model Tank
3400s	110s

Figure 7: The formation time of the liquid in the full-scale tank and the model tank.

Eqn. 3 is valid for contact angles less than 90° [Dodge, 2001]. Formation times are independent of h/R over the range (0.8-1.6), and can be estimated from Eqn. 3 for both full-scale and model tank geometries. Characteristic times are shown in Fig. 7.

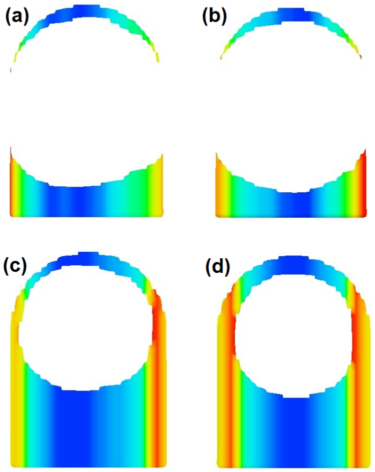


Figure 8: (a) full-scale tank at h/R =0.8; (b) model tank ath/R =0.8; (c) full-scale tank at h/R =1.6; (d) model tank at h/R =1.6.

Since the formation time for the scale tank exceeds 25s , it would have been impossible for us to achieve the zero-g free surface configuration on the zero-g aircraft. Instead, FLOW-3D was used to analyze the zero-g free surface configurations of the liquid in the model tank as well as the full-scale tank.

The zero-g free surface configurations that we observed were not what was expected. We expected the fluid to slightly wick-up the sides of the tank and form a spherical depression in the center of the tank. However, the results were drastically different. The fluid in both the model and the full-scale tank formed a zero-g free surface configuration with a ”double interface”, illustrated in Fig. 8 (a) and (b). This double interface formed at fill levels of less than 1.4. The remaining fill levels exhibited a different configuration. Fig. 8 (c) and (d), depicts a spherical interface at fill levels of 1.4 and 1.6. Again, this differs from our expected results.

8 Summary and Conclusions

We have performed experimental and numerical investigations of slosh modes and free-surface configurations of propellant simulants in reduced and zero-g environments. Experimental measurements of anti-symmetric slosh modes agree well with both theoretical predictions and computational models using Flow-3D.

Free-surface formation times and configurations were not accessible to experiment due to the limited time period of weightlessness provided by parabolic flights. However, in the context of CFD investigations, we did find a new and unexpected free-surface configuration after a step-wise reduction in gravity from 1-g to zero-g in both full-scale and model tank geometries. This new configuration consists of two, often separated, fluid volumes resident at the top and bottom of the tank. The fluid volumes enclose a roughly spherical void volume. These results may have bearing on mass gauging technologies in cylindrical tanks, and are worthy of further investigation.

Finally, we establish, using CFD, that free-surface formation times in the full-scale Orion down-stream propellant tanks should be on the order of 3400 seconds. This results suggests that there may be considerable time between main-engine cut-off and propellant equilibrium during which the propellant is in a dynamic state.

References

[Abramson, 1966] Abramson, H. Norman,“The Dynamic Behavior of Liquids in Moving Containers,” National Aeronautics and Space Administration, Washington, D.C. (1966)

[Dodge, 1967] Dodge, F., and Garza, L., Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravity, Trans. ASME J. of Appl. Mech., **34** (1967).

[Dodge, 2001] Dodge, Franklin T., “The New Dynamic Behavior of Liquids in Moving Containers,” Southwest Research Institute, San Antonio, Texas. (2001)

[Graham, 1952] Graham, E. W. and A. M. Rodriguez. “The Characteristics of Fuel Motion Which Affect Airplane Dynamics,” Journal of Applied Mechanics **123** (1952): 381-388.

[Hirt, C.W., 2009] Hirt, C.W. (2009). FLOW-3D (Version 9.4) [Computer software], Santa Fe, NM: Flow Science.

[NASA, 2010] “Space Flight Systems @ GRC: Orion Project Office, NASA Website, Jan. 12, 2010. http://spaceflightsystems.grc.nasa.gov/Orion/

[Pal et al, 2001] Pal, N. C., S. K. Bhattacharyya and P. K. Sinha. “Experimental Investigation of Slosh Dynamics of Liquid-Filled Containers,” Experimental Mechanics 41 (2001): 63-69.

[Robinson,1964] Robinson, H.G.R. and C.R. Hume. “Europa I: Flight Trial of F1- 5th June, 1964, 1964.

[Salzman, 1969] Salzman, Jack A. and William J. Masica. “Lateral Sloshing in Cylinders under Low-Gravity Conditions,” Technical Note, 1969.

[Space Exploration Technologies Corp., 2007] Space Exploration Technologies Corp. “Demo Flight 2 Flight Review Update, June 15, 2007.

[Sumner et al, 1964] Sumner, Irving E., Andrew J. Stofan and Daniel J. Shramo. “Experimental Sloshing Characteristics and a Mechanical Analogy of Liquid Sloshing in a Scale-Model Centaur Liquid Oxygen Tank,” 1964.

[Vreeburg, 2005] Vreeburg, Jan P.B. “Spacecraft Maneuvers and Slosh Control, in IEEE Control Systems Magazine, June 2005.

[Wade, 2010] Wade, Mark. “Cape Canaveral LC5, Encyclopedia Astronautica. 7 June 2010 http://www.astronautix.com/sites/capallc5.htm.